

# Globular Clusters as Microlensing Targets

Geza Gyuk<sup>1</sup> and Gilbert P. Holder<sup>2</sup>

<sup>1</sup>*S.I.S.S.A., via Beirut 2–4, 34014 Trieste, Italy*

<sup>2</sup>*Department of Astronomy & Astrophysics, The University of Chicago, Chicago, IL 60637*

Received \*\*\*

## ABSTRACT

We investigate the possibility of using globular clusters as targets for microlensing searches. Such searches will be challenging and require more powerful telescopes than now employed, but are feasible in the 0 future. Although expected event rates are low, we show that the wide variety of lines of sight to globular clusters greatly enhances the ability to distinguish between halo models using microlensing observations as compared to LMC/SMC observations alone.

**Key words:** Galactic halo: microlensing: dark matter: globular clusters

## 1 INTRODUCTION

The over 15 microlensing events observed towards the LMC represent a triumph of experimental perseverance in the face of seemingly insurmountable odds (Axelrod 1997). However, microlensing has perhaps opened up more questions than it has resolved. What are the lenses? Where are they? What fraction of the halo do they constitute? Are they really part of the extended halo? Even if we could unequivocally state that the answer to the last question is “yes”, there are still a number of unanswered questions. Present observations can tell us very little about one of the most important issue: the structure of the baryonic halo. What is the shape of the dark baryonic halo? What is the core radius? Is the halo really a  $1/r^2$  halo? Indeed, rather than being elucidated, these issues of structure cloud the interpretation of the events observed (Gates et al. 1996). Studies show that this is inevitable even with a very large number of events (Markovic & Sommer-Larsen 1997). The difficulty in obtaining information on the halo structure stems from two sources. First, the basic microlensing degeneracies prohibit obtaining direct distance information along the line of sight. Second, even if such information could be obtained, inverting one dimensional data to obtain a three dimensional distribution is risky and prone to error.

Two strategies can be employed to address these problems: using parallax measurements to break the basic degeneracy (Gould 1992) and using multiple lines of sight to extract structure information directly. A parallax satellite (or better a pair) would allow us to determine the distances to individual lenses and hence have information about the distribution of mass along the line of sight to the LMC. Given the expense of satellites, and the difficulties in translating this to three dimensional information, it is reasonable to more fully explore the second possibility. This paper will

look at the benefits of multiple lines of sight. They allow a more direct mapping of the variation of density with position and thus a determination of such quantities as halo flattening. Ideally the two methods would complement each other allowing a full mapping of the halo with greatly lessened theoretical uncertainty.

A variety of possibilities come to mind when alternate lines of sight are contemplated:

- (i) Andromeda (M31)
- (ii) dSph
- (iii) Globular clusters
- (iv) bulge
- (v) spiral arms

Of these, the first provides only a single line of sight through *our* halo and of course will be complicated (from our point of view) by self lensing. The second possibility is more attractive. Dwarf spheroidals have a large number of stars in an environment where crowding is not expected to be a problem. Unfortunately they are both distant and few. Further, some are not even as luminous as large globular clusters. Discarding the most problematic, only a handful remain as likely candidates, reducing their value as probes of varied lines of sight. Finally, dwarf spheroidals are not well-understood. Their observed velocity dispersions seem to either require a substantial dark matter halo for each dSph or else indicate that they are extended structures formed from the tidal disruption of a larger system (see e.g. (Gallagher & Wyse 1994)). In either case, self-lensing may be an important consideration.

The last two directions are expected (and observed in the case of the bulge) to be dominated by lensing from non-halo populations (Alcock et al. 1997a 1997a). Information about halo properties may be difficult to disentangle from the tail of the disk/bulge lensing distribution. Globulars are

well studied systems, do not have halos of their own (Moore 1996), and are small enough so that self lensing is negligible. Further, they are abundant, relatively close (but not too close) and contain a respectable number of stars.

The rest of this paper is organized in four sections. The first discusses the selection of appropriate clusters and touches briefly on the expected number of stars observable. The next two sections set up characteristic galaxy models we will explore, discuss how effective cluster microlensing is in distinguishing between them and compare this to observations of the SMC. Finally, we conclude with a summary of the expected benefits of cluster microlensing and what it will take to make it happen.

## 2 SELECTION OF GLOBULAR CLUSTERS

Observing globular clusters for microlensing will be difficult. The number of stars is limited both by the low masses of clusters and the highly crowded conditions. We discuss these challenges in more detail later, but for now it should be noted that the ability to observe lensing events in a globular cluster is only half the story. The other half is whether such observations are worth the effort: will the information from observations along multiple lines of sight yield enough additional information as to the structure of the halo? Nevertheless, it is clear that not all globular clusters can be used and that the best candidates must be selected.

We examined the globular cluster catalog made available by William E. Harris (McMaster University) at “<http://www.physics.mcmaster.ca/Globular.html>”. To be useful for a microlensing search, a globular cluster must satisfy a number of criteria. First, it must have a reasonable number of potentially observable stars. Second, the optical depth must be relatively large, and third the microlensing rate due to halo objects must not be swamped by events due to disk and bulge lenses. We examine each of these constraints in turn.

Ideally, we would have simulated a microlensing search to each of the  $\approx 150$  known globular clusters, creating images based on realistic cluster models (core radius, tidal radius, luminosity function, etc.) and observational parameters (seeing, aperture etc). These simulated images could then be analysed with a photometric pipeline to determine the effective number of stars observable for each cluster. Such a procedure would be very complex and time consuming. Furthermore it would be strongly dependent on the telescopic parameters and the observing strategies used. We adopted a very different procedure. Clusters were cut on distance modulus and total luminosity. Estimates based on standard globular cluster luminosity functions indicate that a  $M_V = -7.5$  cluster should have  $\approx 200,000$  stars above  $M_V = 10$ . We assume such stars can be observed out to a distance modulus,  $m_D$ , of 17.5. We discuss the challenges of observing stars 200 times fainter than present microlensing searches in the our final section. We thus consider only clusters with both distance modulus,  $m_D < 17.5$  and  $M_V < -7.5$ . Many stars will be unobservable due to crowding. On the other hand, the typical cluster we select will be both brighter and closer, increasing the number of stars above the limiting magnitude. As a reasonable compromise we adopt 100,000 stars for each

[hb]

**Table 1.** Globular clusters that passed distance, brightness and latitude cuts. Distances from the Sun are in kpc. Visual luminosity ( $M_V$ ) and distance modulus ( $m_D$ ) are in magnitudes. The optical depth is for a standard halo and is in unit of  $10^{-8}$ .

Cluster	$D_\odot$	l	b	$M_V$	$m_D$	$\tau$
NGC 1261	15.2	270.5	-52.10	-7.68	15.97	6.4
NGC 1851	11.7	244.5	-35.00	-8.26	15.40	3.6
NGC 1904	12.2	227.2	-29.40	-7.73	15.46	3.4
NGC 2808	8.9	282.2	-11.30	-9.26	15.46	3.2
NGC 5024	18.1	333.0	79.80	-8.70	16.31	9.0
NGC 5272	9.7	42.2	78.70	-8.77	14.96	3.6
NGC 5286	11.3	311.6	10.60	-8.67	16.01	7.4
NGC 5634	24.6	342.2	49.30	-7.64	17.11	21.4
NGC 5986	10.0	337.0	13.30	-8.31	15.83	8.7
NGC 6093	8.4	352.7	19.50	-7.85	15.18	6.2
NGC 6205	28.3	73.6	40.30	-7.90	17.29	15.8
NGC 6325	8.1	5.5	10.70	-7.94	15.66	6.2
NGC 6342	13.8	6.7	10.20	-8.35	16.60	21.0
NGC 6388	8.4	21.3	14.80	-8.89	16.48	5.9
NGC 6569	12.5	342.1	-16.40	-7.56	15.83	14.3
NGC 6712	25.4	5.6	-14.10	-9.89	17.49	46.0
NGC 6717	8.2	0.1	-17.30	-7.67	14.68	6.1
NGC 6838	17.7	20.3	-25.70	-8.21	16.73	21.5
NGC 7006	10.0	65.0	-27.30	-9.07	15.27	4.5
NGC 7078	11.1	53.4	-35.80	-8.90	15.37	5.9

cluster. We discuss how our results change as this number is increased or decreased.

We want our candidate clusters to be worth observing: Clusters with a very low optical depth in *all* models will give us little leverage for distinguishing between models. Since we do not know a priori what models might be interesting we used a halo independent measure, the heliocentric distance. Clusters close to the observer will have narrow, short microlensing tubes and hence low optical depths. Conversely, distant clusters are much more likely to have high optical depths. Further, local clusters are much less useful as a probe of the global structure of the halo even if they have a high optical depth. We thus adopted a cut on the distance to the globular clusters,  $R_s > 8$  kpc. Clusters closer than this had negligible lensing.

Finally, we wished to concentrate on the halo. Thus clusters for which non-halo lensing would dominate had to be removed. One could calculate the expected ratio of disk/bulge lensing versus halo lensing, but this procedure is fraught with the uncertainties of disk and bulge models. We took a simpler approach, eliminating those clusters lying within  $10^\circ$  of the galactic plane.

Twenty clusters survived these cuts with an average luminosity  $M_V \approx -8.5$  and distance modulus  $m_D \approx 16$ . Optical depths for a standard halo model normalized to  $\tau_{LMC} = 2.5 \times 10^{-7}$  ranged from 0.3 to  $4.6 \times 10^{-7}$ . The clusters are listed in Table 1.

## 3 MODEL DISCRIMINATION

We know little about the detailed structure of dark halos. Rotation curves probe the radial profiles of galaxies, but it is difficult to determine the relative importance of the dark and luminous material. Further, rotation curves can only provide information in one direction. Flaring of HI gas layers in disks

**Table 2.** Characteristic models used. The core radii are given in kpc.

Model	Core	Index	Axis Ratio	
A	5.0	2.0	1.0	Standard halo model
B	20.0	2.0	1.0	large core model
C	5.0	2.0	0.6	flattened model
D	1.0	3.0	1.0	non-halo model
E	-	-	-	debris model

would seem to be a good probe of the shape of the potential when used in conjunction with the rotation curves (Olling 1996), but seem to give anomalous results that are difficult to reconcile with stability concerns or other tracers of the potentials. Polar ring galaxies provide a unique opportunity to probe the shapes of dark matter halos in that there are orthogonal probes of the potential (Sackett et al. 1994), but the details of polar rings are uncertain and these galaxies are almost certainly deeply disturbed systems. Weak lensing has not yet borne fruit while simulations are not clear and could be lacking resolution and/or physics.

Expectations for a baryonic halo are even more uncertain. A very rough idea of the uncertainties involved can be gained by adopting the following parametrized model for the halo:

$$\rho = \rho_0 \frac{a^\beta + r_0^\beta}{a^\beta + R^\beta + (z/q)^\beta}. \quad (1)$$

Such a model has 4 unknowns corresponding to the mass, flattening, core radius and radial fall-off of the halo. Clearly the parameter space represented by such models is very large. Since the amount of data from cluster lensing will be small measuring precise values for the parameters is not expected. Instead, we will concern ourselves with how well cluster lensing can discriminate between classes of models. We pick representative models illustrating various portions of the parameter space.

Our models are summarized in Table 2. The first model is the standard halo model of Griest (1991), with an isotropic velocity dispersion  $\sigma \sim 156$  km/s. The second is a similar model, but with a much larger core radius. Third is a flattened halo as suggested by polar ring and HI flaring studies, with the velocity dispersion reduced in one dimension according to the tensor virial theorem. Fourth is a more steeply declining halo based on the stellar halo, with a velocity dispersion given by  $\sigma \sim 127$  km/s. This model is supplemented by a heavy thick disk which does about 30% of the lensing. As the lenses are not in the dark halo proper, we call this the non-halo model. Finally, fifth is a model with no MACHOs in the halo at all. The LMC lensing is provided by a tidal tail or a disrupted dwarf galaxy in the line of sight as suggested by Zhao (1997). All models are constructed to have  $\tau_{LMC} = 2.0 \times 10^{-7}$  and  $\Gamma_{LMC} = 4.0 \times 10^{-14} \text{ s}^{-1}$ . Microlensing observations towards the LMC alone will be incapable of distinguishing between these models since the distribution of lens masses is unknown.

To determine how well cluster lensing can distinguish between models, we proceed in the following manner. First, we pick a “true” model S from the set described above. After computing the microlensing rate towards each target under this model we generate a realization of S. That is to say we pick an observed number of events for each target based on

the rate and ten years of observation, using Poisson statistics. For each realization we compute the likelihood for each of our models. The most likely model will not necessarily be the “true” model. After generating many (100,000) realizations we can build up the probability  $P(T)$  that the model S will be identified by a microlensing experiment as the model T. Repeating but with a different “true” model we build the full matrix  $P(S,T)$  which gives the chance that the real galaxy S will appear to the observers as T. If  $P(S,T)$  is diagonal then we know that the observations are doing a good job of distinguishing models. If on the other hand, it is far from diagonal, then observations are doing a poor job and misidentifications are frequent: the data cannot even distinguish between, for example, a flattened halo and a spherical halo.

We present results from a number of scenarios: LMC/SMC lensing alone, LMC and globular cluster lensing, and LMC/SMC/cluster/dSph lensing. For the dSph lensing, we looked at lensing information that could be gained from looking at Fornax, Sculptor, Sextans and Ursa Minor. The other dSph’s were either too far, too faint, or some combination of the two to be useful. We take the effective number of stars in the SMC to be  $2.0 \times 10^6$ . We also show how these the effectiveness of globular cluster lensing varies with number of observable stars.

## 4 RESULTS

It has been suggested that SMC lensing can break the degeneracy between flattened and spherical halos (eg. Sackett & Gould 1993). Unfortunately, for realistic event rates the time required is large. As can be seen in Table 3, for a ten year experiment LMC/SMC observations can correctly select the flattened model only  $\approx 60\%$  of the time. Examination of the likelihoods directly shows that even when the correct model is selected, the margin of probability is small with spherical models and large core radii models only slightly less preferred. When the “true” model has a large core SMC lensing performs abysmally. Indeed, most of the time another model is preferred. As is true of the LMC, the line of sight towards the SMC is most sensitive at large galactocentric distances, where the effect of a larger core radius is small. As expected, SMC lensing does better for non-halo models. Here the direction of the SMC line of sight closer to the Galactic center allows it to penetrate into the dense inner regions. However, there is still a reasonable chance (30%) that an unexpectedly high amount of SMC lensing mimics one of the other models. Further, examination of the likelihoods again shows that the probabilities are not sharply peaked on the non-halo models. Thus our confidence in this determination will not be high. The debris models are always correctly identified. LMC/SMC lensing in general does not fare well in distinguishing between models because it only probes two lines of sight. This is particularly worrisome if self lensing is important as has been suggested for the SMC (Palanque-Delabrouille 1997). Even a small amount of unknown self lensing is capable of throwing the model determinations into grave doubt. Furthermore, if the detailed structure of the baryonic halo is lumpy, as suggested in some models, the determinations become even more uncertain. Microlensing

**Table 3.** Discrimination matrix for five scenarios. See text and Table 2 for explanation of the models used.

SMC only (2.0e6 stars)					
	A	B	C	D	E
A	0.29	0.23	0.20	0.29	0.00
B	0.22	0.31	0.33	0.14	0.00
C	0.10	0.19	0.64	0.06	0.00
D	0.19	0.06	0.07	0.69	0.00
E	0.00	0.00	0.00	0.00	1.00

G.Clusters (2.0e6 stars)					
	A	B	C	D	E
A	0.63	0.04	0.33	0.00	0.00
B	0.03	0.97	0.00	0.00	0.00
C	0.35	0.01	0.64	0.00	0.00
D	0.00	0.00	0.00	1.00	0.00
E	0.00	0.00	0.00	0.00	1.00

SMC, G. Clusters and dSph					
	A	B	C	D	E
A	0.78	0.03	0.19	0.00	0.00
B	0.02	0.98	0.00	0.00	0.00
C	0.18	0.01	0.82	0.00	0.00
D	0.00	0.00	0.00	1.00	0.00
E	0.00	0.00	0.00	0.00	1.00

G. Clusters (1.0e6 stars)					
	A	B	C	D	E
A	0.52	0.11	0.37	0.00	0.00
B	0.07	0.92	0.01	0.00	0.00
C	0.35	0.06	0.59	0.00	0.00
D	0.00	0.00	0.00	1.00	0.00
E	0.00	0.00	0.00	0.00	1.00

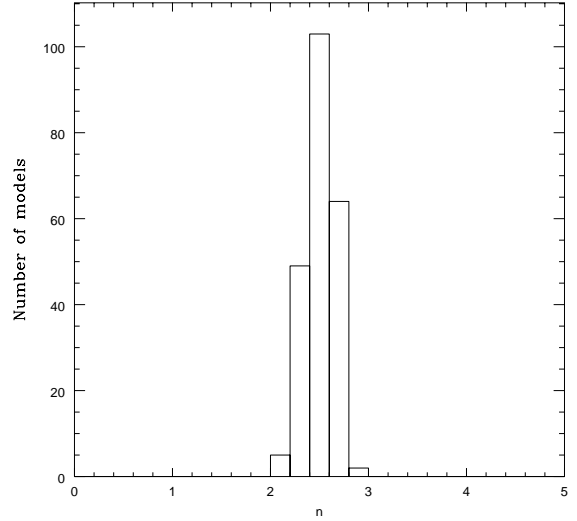
  

G. Clusters (4.0e6 stars)					
	A	B	C	D	E
A	0.72	0.01	0.28	0.00	0.00
B	0.00	1.00	0.00	0.00	0.00
C	0.29	0.00	0.71	0.00	0.00
D	0.00	0.00	0.00	1.00	0.00
E	0.00	0.00	0.00	0.00	1.00

towards the SMC appears to be a poor tool for elucidating halo structure.

Globular cluster microlensing can avoid some of these problems. First of all, quick calculations show that  $\tau_{self} \ll 10^{-8}$  for all globular clusters. Thus, self lensing will be negligible. Second, since many more lines of sight are involved, lumpiness in the detailed distribution of the mass will be largely smoothed over. The figures for LMC/globular cluster lensing shown in Table 3 should therefore be more robust than the corresponding figures for LMC/SMC lensing.

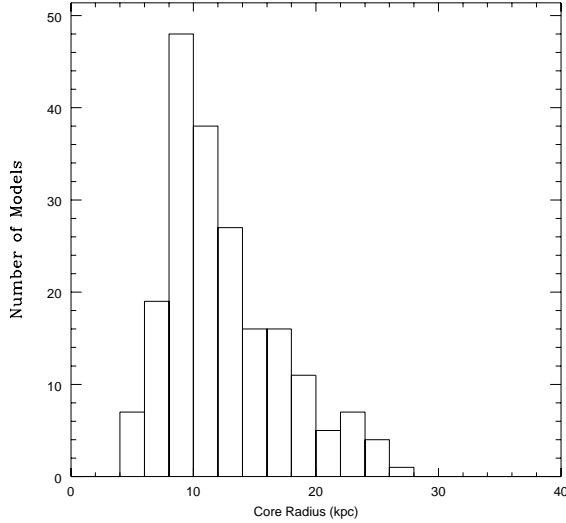
A quick examination shows that globular cluster lensing is much better at distinguishing between models with different core radii. This is quite understandable: globular clusters probe precisely the region where differences in the core are most apparent. Similarly, the selection of the non-halo models certain. Models with a large power-law index predict

**Figure 1.** Distribution of best-fit power law indices for a true model of  $n=2.5$  and LMC/SMC/cluster/dSph lensing. Clusters are assumed to have 100,000 stars monitorable.

much higher lensing towards the globular clusters making the distinction very easy and certain. LMC/globular cluster observations do not fare better than LMC/SMC observations at distinguishing flattened models. This is because only a few clusters are at high galactic latitude. As before, the debris models are firmly ruled out. We also examined a scenario where the SMC, globular clusters and four dSph galaxies were all observed. For these purposes we assumed that it was possible to monitor 500,000 stars in each dSph. Results are shown in the third part of Table 3. The improvement in the determination of the flattening is considerable due to the relatively high latitudes of the dSph's.

Since the core radius and the power-law index are so easily distinguished by the full set of targets, we investigated the question of how well quantitative information could be obtained. We picked a standard model with  $n=2.5$ . Realizations of this model were then compared to models where the optical depth towards the LMC was held fixed but the power law index was allowed to float. Figure 1 shows the distribution of power law indices inferred. The peak is clearly around the “true” value with a small ( $\approx 0.2$ ) variance. The concentration of the globular clusters towards the Galactic Center allows very accurate determination of this parameter. A similar test was performed for the core radius, this time with a core of 12 kpc. Figure 2 shows the distribution of inferred values. Note that the distribution is not quite as tight ( $\sigma \approx 5$  kpc), but still allows fairly accurate determination of the core radius.

Finally, we examined how much our results depended on the number of stars observable per cluster. Table 4 shows the results of LMC/globular cluster lensing for 50,000 and 200,000 stars per cluster. We see that the results are not strongly sensitive to increases in the number of stars observed, although marginal improvement is obtained. When the number of stars is decreased, however, the returns on cluster lensing are lower. Nevertheless, clusters can still discriminate between models better than LMC/SMC lensing



**Figure 2.** Distribution of best-fit core radii for a true model of  $a=12$  kpc and LMC/SMC/cluster/dSph lensing. Clusters are assumed to have 100,000 stars monitorable.

especially when the possible problems with LMC/SMC lensing are considered. Globular cluster microlensing is a worthwhile investment, even at lower numbers of effective stars.

## 5 CONCLUSIONS

Globular cluster microlensing searches are much better for determining important halo parameters than LMC/SMC measurements alone. Although few events are involved, the diverse lines of sight allow far greater leverage on halo structure parameters. In particular, the power-law index and the core radius are readily accessible to cluster data.

The importance of diverse lines of sight has already been demonstrated: reports of a microlensing event seen towards the SMC by both the MACHO and EROS collaborations (Palanque-Delabrouille 1997; Alcock et al. 1997c 1997c) suggest that the debris models for LMC lensing are not viable. Caution must be taken however, as the self lensing due to the SMC could cloud this interpretation. The small size and low self-lensing of the globular clusters is a definite advantage in this respect.

The faintness of the typical globular cluster stars ( $M_V \approx 26$ ), and the highly crowded conditions ( $>100$  stars/arcsec<sup>2</sup> at the core) both make microlensing observations difficult. This suggests that the best bet for cluster microlensing studies would be a large ( $\approx 8m$ ) telescope with excellent seeing ( $< 0.5''$ ), possibly achieved with adaptive optics. Telescopes of this type, such as the SUBARU, are just now coming on-line. Indeed, Yanagisawa & Muraki (1997), have done a preliminary study and conclude that the SUBARU telescope should be able to monitor about 200,000 stars each in Pal 8 and NGC6453 with 10 second exposures. Longer exposures and stellar templates provided by HST may be able to push this number up considerably. Even if such large telescopes and high resolution are not available, application of the pixel lensing technique may allow monitoring of sufficient stars. Rhoads & Malhotra (1997) calculate

that pixel lensing can allow 200,000 star equivalents to be monitored in M15 and an average over all globular clusters of about 60,000. We note that our clusters are considerably more luminous than the average cluster. Finally, it is important to realize that such experiments have *already* been performed! Mighell et al. (1992) reported two nights of observations toward Omega Centauri with the Anglo-Australian telescope. Although no events were detected, 50,000 stars in a 12.5' field were monitored with 10 sec exposures. In an ongoing effort to search for variable stars, the OGLE collaboration has been examining portions of Omega Centauri and 47 Tuc (Kaluzny et al. 1996). With 500 sec exposures in 1.6" seeing they follow about 30,000 stars in Omega Centauri. In light of these numbers, the target figure of 100,000 stars per cluster seems reasonable.

The challenges involved in cluster microlensing searches should not be underestimated: following millions of very faint stars in extremely crowded fields scattered over a large part of the sky will require dedication, both of telescope time and its practitioners. The telescopes and techniques are both at the cutting edge of astronomy. However, optimism is warranted: 10 years ago microlensing was a pipe dream, now seven collaborations are actively pursuing it and millions of stars are monitored nightly. We must be bold in proposing and following up new ideas.

## ACKNOWLEDGEMENTS

After this work was completed we received a preprint (astro-ph/9710231, Rhoads & Malhotra 1997) which reaches similar conclusions.

## REFERENCES

- Alcock, C., et al., 1997a, ApJ, 479, 119.
- Alcock C. et al., 1997b, ApJ, 486, 697
- Alcock C., et al., 1997c, astro-ph/9708190.
- Axelrod T., 1997, seminar at the Aspen Center for Physics.
- Gallagher, J., & Wyse, R., 1994, PASP, 106, 1225.
- Gates E., Gyuk G., Turner M.S., 1996, Phys. Rev. D, 53, 4138
- Gould, A., 1992, ApJ, 392, 442.
- Griest K., 1991, ApJ, 366, 412
- Kaluzny, J., Kubiak, M., Szymanski, M., Udalski, A., Krzemiński, W., & Mateo, M., 1996, A&AS, 120, 139.
- Markovic, D., & Sommer-Larsen J., 1997, MNRAS, 288, 733.
- Mighell, K., Freeman K., Silk, J., & Vanderberg D., 1992, BAAS, 181, #43.04.
- Moore, B., 1996, ApJ, 461, 13.
- Olling R. P., 1996, AJ, 112, 481
- Palanque-Delabrouille, N., et al., 1997, astro-ph/9710194.
- Rhoads, J. & Malhotra S., 1997, astro-ph/9710231.
- Sackett, P. & Gould, A., 1993, ApJ, 419, 648.
- Sackett P., Rix H., Jarvis B.J., Freeman K.C., 1994, ApJ, 436, 629
- Yanagisawa, T. & Muraki, Y., 1997, presentation at the Third International Microlensing Workshop, Notre Dame.
- Zhao, H., 1997, astro-ph/9703097.